

SUSY DARK MATTER

Achille Corsetti and Pran Nath

*Department of Physics, Northeastern University,
Boston, MA 02115-5005, USA*

Abstract

Several new effects have been investigated in recent analyses of supersymmetric dark matter. These include the effects of the uncertainties of wimp velocity distributions, of the uncertainties of quark densities, of large CP violating phases, of nonuniversalities of the soft SUSY breaking parameters at the unification scale and of coannihilation on supersymmetric dark matter. We review here some of these with emphasis on the effects of nonuniversalities of the gaugino masses at the unification scale on the neutralino-proton cross-section from scalar interactions. The review encompasses several models where gaugino mass nonuniversalities occur including SUGRA models and D brane models. One finds that gaugino mass nonuniversalities can increase the scalar cross-sections by as much as a factor of 10 and also significantly extend the allowed range of the neutralino mass consistent with constraints up to about 500 GeV. These results have important implications for the search for supersymmetric dark matter.

1 INTRODUCTION

Over the recent past there has been considerable experimental activity in the direct detection of dark matter ^{1, 2)} and further progress is expected in the ongoing experiments ^{1, 2, 3)} and new experiments that may come online in the future ⁴⁾. At the same time there have been several theoretical developments which have shed light on the ambiguities and possible corrections that might be associated with the predictions on supersymmetric dark matter. These consist of the effects on the dark matter analyses of wimp velocity ^{5, 6, 7)} and of the rotation of the galaxy ⁸⁾, the effects of the uncertainties of quark densities ^{9, 10, 11)} and the uncertainties of the SUSY parameters ¹²⁾, effects of large CP violating phases ^{13, 14)}, effects of scalar nonuniversalities ¹⁵⁾, effects of nonuniversalities of gaugino masses ¹¹⁾ and effects of coannihilation ¹⁶⁾. In this paper we will discuss some of these briefly but mainly focus on the effects of nonuniversalities of the gaugino masses on dark matter. In the Minimal Supersymmetric Standard Model (MSSM) there are 32 supersymmetric particles and with R parity conservation the lowest mass supersymmetric particle (LSP) is absolutely stable. In many unified models, such as in the SUGRA models ¹⁷⁾, one finds that the lightest neutralino is the LSP over most of the parameter space of the model. Thus the lightest neutralino is a candidate for cold dark matter. The quantity that constrains supersymmetric models is $\Omega_\chi h^2$ where $\Omega_\chi = \rho_\chi/\rho_c$ where ρ_χ is the density of relic neutralinos at the current temperatures, and $\rho_c = 3H_0^2/8\pi G_N$ is the critical matter density, and h is the Hubble parameter H_0 in units of 100 km/sMpc. The most recent measurements of h from the Hubble Space Telescope give ¹⁸⁾

$$h = 0.71 \pm 0.03 \pm 0.07 \quad (1)$$

Similarly the most recent analyses of Ω_m give ¹⁹⁾

$$\Omega_m = 0.3 \pm 0.08 \quad (2)$$

If we assume that the component of Ω_B in Ω_m is $\Omega_B \simeq 0.05$ which appears reasonable, then this leads to the result $\Omega_\chi h^2 = 0.126 \pm 0.043$. Perhaps a more cautious choice of the range would be a $\sim 2\sigma$ range which gives

$$0.02 \leq \Omega_\chi h^2 \leq 0.3 \quad (3)$$

The quantity of interest theoretically is

$$\Omega_\chi h^2 \cong 2.48 \times 10^{-11} \left(\frac{T_\chi}{T_\gamma} \right)^3 \left(\frac{T_\gamma}{2.73} \right)^3 \frac{N_f^{1/2}}{J(x_f)} \quad (4)$$

Here T_f is the freeze-out temperature, $x_f = kT_f/m_{\tilde{\chi}}$ where k is the Boltzman constant, N_f is the number of degrees of freedom at the time of the freeze-out, $(\frac{T_{\chi}}{T_{\gamma}})^3$ is the reheating factor, and $J(x_f)$ is given by

$$J(x_f) = \int_0^{x_f} dx \langle \sigma v \rangle(x) GeV^{-2} \quad (5)$$

where $\langle \sigma v \rangle$ is the thermal average with σ the neutralino annihilation cross-section and v the neutralino relative velocity.

2 Detection of Milky Way wimps

Both direct and indirect methods are desirable and complementary for the detection of Milky Way wimps. We shall focus here on the direct detection. In this case the fundamental detector is the quark and the relevant interactions are the supergravity neutralino-quark-squark interactions. The scattering of neutralinos from quarks contains squark poles in the s channel and the Z boson and the Higgs boson (h, H^0, A^0) poles in the t channel. Since the wimp scattering from quarks is occurring at rather low energies one may, to a good approximation, integrate on the intermediate squark, Z and Higgs poles to obtain a low energy effective Lagrangian which gives a four-Fermi interaction of the following form

$$\mathcal{L}_{eff} = \bar{\chi}\gamma_{\mu}\gamma_5\chi\bar{q}\gamma^{\mu}(AP_L + BP_R)q + C\bar{\chi}\chi m_q\bar{q}q + D\bar{\chi}\gamma_5\chi m_q\bar{q}\gamma_5q \quad (6)$$

The contribution of D is generally small and thus the scattering is effectively governed by the terms A,B and C. Analysis of dark matter is affected by several factors. We discuss these briefly below.

2.1 Uncertainties in wimp density and velocity

Two of the quantities that control the detection of dark matter are the wimp mass density and the wimp velocity. Estimates of Milky Way wimp density lie in the range ²⁰⁾ $\rho_{\chi} = (0.2 - 0.7)GeVcm^{-3}$ and the event rates in the direct detection depend directly on this density. A second important factor regarding wimps that enters in the dark matter analyses is the wimp velocity. One typically assumes a Maxwellian velocity distribution for the wimps and the current estimates for the rms wimp velocity give $v = 270 km/s$ with, however, a significant uncertainty. Estimates for the uncertainty lie in the range of $\pm 24 km/s$ to $\pm 70 km/s$ ²¹⁾. A reasonable estimate then is that the rms wimp velocity lies in the range ²¹⁾

$$v = 270 \pm 50 km/s \quad (7)$$

Analyses including the wimp velocity variations show that the detection rates can have a significant variation, i.e., a factor of 2-3 on either side of the central values ⁷⁾.

2.2 Effects of uncertainties of quark densities

The scattering of neutralinos from quarks are dominated by the scalar interaction which is controlled by the term C in Eq.(6). The dominant part of the scattering thus arises from the scalar part of the $\chi - p$ cross-section which is given by

$$\sigma_{\chi p}(scalar) = \frac{4\mu_r^2}{\pi} \left(\sum_{i=u,d,s} f_i^p C_i + \frac{2}{27} \left(1 - \sum_{i=u,d,s} f_i^p \right) \sum_{a=c,b,t} C_a \right)^2 \quad (8)$$

Here μ_r is the reduced mass in the $\chi - p$ system and f_i^p (i=u,d,s quarks) are quark densities inside the proton defined by

$$m_p f_i^p = \langle p | m_{qi} \bar{q}_i q_i | p \rangle \quad (9)$$

There are significant uncertainties in the determination of f_i^p . To see the range of these uncertainties it is useful to parametrize the quark densities so that ¹¹⁾

$$\begin{aligned} f_u^p &= \frac{m_u}{m_u + m_d} (1 + \xi) \frac{\sigma_{\pi N}}{m_p} \\ f_d^p &= \frac{m_d}{m_u + m_d} (1 - \xi) \frac{\sigma_{\pi N}}{m_p} \\ f_s^p &= \frac{m_s}{m_u + m_d} (1 - x) \frac{\sigma_{\pi N}}{m_p} \end{aligned} \quad (10)$$

where we have defined

$$\begin{aligned} x &= \frac{\sigma_0}{\sigma_{\pi N}} = \frac{\langle p | \bar{u}u + \bar{d}d - 2\bar{s}s | p \rangle}{\langle p | \bar{u}u + \bar{d}d | p \rangle}, \quad \xi = \frac{\langle p | \bar{u}u - \bar{d}d | p \rangle}{\langle p | \bar{u}u + \bar{d}d | p \rangle} \\ \sigma_{\pi N} &= \langle p | 2^{-1} (m_u + m_d) (\bar{u}u + \bar{d}d) | p \rangle \end{aligned} \quad (11)$$

The current range of determinations of $\sigma_{\pi N}$ give ¹¹⁾

$$\sigma_{\pi N} = 48 \pm 9 \text{ MeV}, \quad x = 0.74 \pm 0.25, \quad \xi = 0.132 \pm 0.035 \quad (12)$$

With the above range of errors one finds that f_i^p lie in the range

$$f_u^p = 0.021 \pm 0.004, \quad f_d^p = 0.029 \pm 0.006, \quad f_s^p = 0.21 \pm 0.12 \quad (13)$$

Of these the errors in f_s^p generates the largest variations. A detailed analysis shows that the scalar cross-section can vary by a factor of 5 in either direction due to errors in the quark densities ¹¹⁾.

2.3 CP violation effects on dark matter

The soft SUSY breaking parameters that arise in supersymmetric theories after spontaneous breaking are in general complex with phases $O(1)$ and can lead to large electric dipole moment of the electron and of the neutron in conflict with current experiment. Recently a cancellation mechanism was proposed as a possible solution to this problem^{22, 23)}. With the cancellation mechanism the total EDM of the electron and of the neutron can be in conformity with data even with phases $O(1)$ and sparticle masses which are relatively light. The presence of large CP phases can affect dark matter and other low energy phenomena. Effects of CP violating phases on dark matter have been investigated for some time¹³⁾ and more recently such analyses have been extended to determine the effects of large CP phases under the cancellation mechanism¹⁴⁾. One finds that the EDM constraints play a crucial role in these analyses. Thus in the absence of CP violating phases one finds that the $\chi - p$ cross-section can change by orders of magnitude when plotted as a function of θ_μ (the phase of μ). These effects are, however, significantly reduced when the constraints arising from the current experimental limits on the electron and on the neutron EDMs are imposed. After the imposition of the constraints the effects of CP violating phases are still quite significant in that the $\chi - p$ cross-section can vary by a factor of ~ 2 . Thus precision predictions of the $\chi - p$ cross-section should take account of the CP phases if indeed such phases do exist in a given model. Indeed many string and D brane models do indeed possess such phases and thus inclusion of such phases is imperative in making predictions for direct detection in such models.

2.4 Effects of coannihilation

The effects of coannihilation may become important when the next to the lowest supersymmetric particle (NLSP) has a mass which lies close to the LSP mass²⁴⁾. The size of the effects is exponentially damped by the factor $e^{-\Delta_i x}$ where $\Delta_i = (m_i/m_\chi - 1)$, $x = m_\chi/kT$ and where m_χ is the LSP mass. Because of this damping the coannihilation effects are typically important only for regions of the parameter space where the constraint $\Delta_i < 0.1$ is satisfied. Some of the possible candidates for NLSP are the light stau $\tilde{\tau}_1$, \tilde{e}_R , the next to the lightest neutralino χ_2^0 , and the light chargino χ_1^\pm . An interesting result one finds is that in mSUGRA the upper limit on the neutralino mass consistent with the current experimental constraints on the relic density is extended from 200 GeV to 600 GeV¹⁶⁾ when the effects of $\chi - \tilde{\tau}$ coannihilation are included. In Secs.(2.6) and (2.7) we will show that the allowed range of the neutralino mass can also be extended by inclusion of nonuniversalities

in the gaugino masses.

2.5 Nonuniversality of scalar masses

The minimal SUGRA model is based on the universality at the GUT scale. This includes the universality of the scalar masses, of the gaugino masses and of the trilinear couplings at the GUT scale. In supergravity unified models the universality of the soft SUSY breaking parameters arises from the assumption of a flat Kahler potential. However, the nature of physics at the GUT/Planck scale is not fully understood and a more general analysis of the soft SUSY breaking sector requires that one work with a curved Kahler potential^{25, 15)}. Such an analysis in general leads to nonuniversalities in the scalar sector of the theory. However, the nonuniversalities in the scalar sector cannot be completely arbitrary as there are very stringent constraints on the system from the limits on the flavor changing neutral currents (FCNC). A satisfaction of the constraints requires essentially a degeneracy in the scalar masses in the first two generations at the GUT scale. However, the constraints on the scalar masses in the Higgs sector and on masses in the third generation are far less severe and one could introduce significant amounts of nonuniversalities in these sectors without violating the FCNC constraints. It is found convenient to parametrize the nonuniversalities in the Higgs sector by δ_1, δ_2 so that at the GUT scale (M_G) one has $m_{H_1}^2 = m_0^2(1 + \delta_1)$, $m_{H_2}^2 = m_0^2(1 + \delta_2)$. Similarly one may parametrize the nonuniversalities in the third generation squark sector by δ_3, δ_4 so that at the scale M_G one has $m_{\tilde{Q}_L}^2 = m_0^2(1 + \delta_3)$, $m_{\tilde{U}_R}^2 = m_0^2(1 + \delta_4)$. These nonuniversalities have a significant effect on the low energy physics. One of the main effects that occurs is through the effect on μ which is determined via the constraint of the radiative breaking of the electro-weak symmetry and is modified in the presence of the nonuniversalities in the Higgs sector and in the third generation sector. To one loop order it is given by¹⁵⁾

$$\mu^2 = \mu_0^2 + \frac{m_0^2}{t^2 - 1}(\delta_1 - \delta_2 t^2 - \frac{D_0 - 1}{2}(\delta_2 + \delta_3 + \delta_4)t^2) + \Delta\mu^2 \quad (14)$$

Here μ_0 is the value of μ in the absence of nonuniversalities, D_0 depends on the top Yukawa coupling and defines the position of the Landau pole, $t \equiv \tan\beta$, and $\Delta\mu^2$ is the loop correction. We note that the entire effect of nonuniversalities is now explicitly exhibited. One finds that the universalities can significantly affect the event rates. The effect on the event rates occurs specifically because of the effect on μ . Thus one finds that for certain regions of the parameter space the nonuniversalities in the Higgs and in the third generation sector make a negative contribution to μ^2

which leads to larger higgsino components for the neutralino. Since in the direct detection the scattering is dominated by the scalar $\chi - p$ cross-section which in turn depends on the product of the gaugino and the higgsino components one finds that a smaller μ leads to larger event rates in the direct detection. A detailed analysis of the effects of nonuniversalities of the scalar masses has been given in Refs. ¹⁵⁾. We will discuss further this phenomena in the context of the nonuniversalities in the gaugino sector in the next section.

2.6 Gaugino nonuniversalities and dark matter in GUT models

Nonuniversality of gaugino masses arises in grand unified models via corrections to the gauge kinetic energy functions ²⁶⁾. Thus in grand unified models a non-trivial gauge kinetic energy function leads to a gaugino mass matrix which has the form ²⁶⁾

$$m_{\alpha\beta} = \frac{1}{4}\bar{e}^{G/2}G^a(G^{-1})_a^b(\partial f_{\alpha\gamma}^*/\partial z^{*b})f_{\gamma\beta}^{-1} \quad (15)$$

As an example if we consider the GUT group to be SU(5) then the gauge kinetic energy function $f_{\alpha\beta}$ transforms as follows

$$(\mathbf{24} \times \mathbf{24})_{symm} = \mathbf{1} + \mathbf{24} + \mathbf{75} + \mathbf{200} \quad (16)$$

where $(\mathbf{24} \times \mathbf{24})_{symm}$ stands for the symmetric product. The term that transforms like the singlet of SU(5) in the gauge kinetic energy function leads to universality of the gaugino masses, while the **24** plet, the **75** plet and the **120** plet will generate corrections to universality. In general one could have an admixture of the various representations and this will lead to gaugino masses of the form

$$\tilde{m}_i(0) = m_{\frac{1}{2}}(1 + \sum_r c_r n_i^r) \quad (17)$$

where n_i^r depend on r and for the representations **1**, **24**, **75**, **210** they are given in Table 1 ²⁷⁾. The nonuniversality of the gaugino masses also leads to corrections of the gauge coupling constants at the GUT scale and in general one has $g_i(M_G) = g_G(1 + \sum_r c'_r n_i^r)$. We note, however, that the coefficients c'_r that enter in g_i are different than those that enter in m_i . This is so because the corrections to g_i involve only the gauge kinetic energy function while the corrections to m_i involve the gauge kinetic energy function as well as the nature of GUT physics.

Table: nonuniversalities at M_X .

SU(5) rep	n_1^r	n_2^r	n_3^r
1	1	1	1
24	-1	-3	2
75	-5	3	1
200	10	2	1

The gaugino sector nonuniversalities affect μ . To exhibit this effect we can expand μ determined via the constraint of the radiative breaking of the electro-weak symmetry in terms of the parameter c_r . One finds the following expansion

$$\tilde{\mu}^2 = \mu_0^2 + \sum_r \frac{\partial \tilde{\mu}^2}{\partial c_r} c_r + O(c_r^2) \quad (18)$$

and for $c_{24} < 0, c_{75} < 0, c_{200} > 0$ one has ¹¹⁾

$$\frac{\partial \mu_{24}^2}{\partial c_{24}} > 0, \frac{\partial \mu_{75}^2}{\partial c_{75}} > 0, \frac{\partial \mu_{200}^2}{\partial c_{200}} < 0 \quad (19)$$

Thus in these cases the nonuniversalities lead to a smaller value of $|\mu|$. Now as already mentioned in the previous section the Higgsino components become more dominant as μ becomes smaller. We can exhibit this analytically for the case when μ is small but we are still in the scaling region ²⁸⁾ where $\mu^2/M_Z^2 \gg 1$. In this case it is possible to analytically investigate the size of the gaugino-Higgsino components X_{n0} of the LSP defined by

$$\chi = X_{10}\tilde{B} + X_{20}\tilde{W}_3 + X_{30}\tilde{H}_1 + X_{40}\tilde{H}_2 \quad (20)$$

where \tilde{B} is the Bino, \tilde{W}_3 is the Wino, and \tilde{H}_1 , and \tilde{H}_2 are the two Higgsinos. In this case one finds that the gaugino components of the LSP are given by $X_{11} \simeq 1 - (\frac{M_Z^2}{2\mu^2})\sin^2\theta_W$, and $X_{12} \simeq \frac{M_Z^2}{2m_{\tilde{\chi}_1}\mu}\sin 2\theta_W \sin\beta$ while the higgsino components are given by ²⁸⁾ $X_{13} \simeq -\frac{M_Z}{\mu}\sin 2\theta_W \sin\beta$, $X_{14} \simeq \frac{M_Z}{\mu}\sin 2\theta_W \sin\beta$. From the above one finds that the Higgsino components have a dependence on the inverse power of μ and thus a smaller μ will lead to a larger scalar $\sigma_{\chi-p}$ cross-section. The literature on the analyses of dark matter relic density ^{29, 30)} and direct detection in MSSM ³¹⁾ and in SUGRA models ³²⁾ is quite extensive ³³⁾. We discuss here the quantitative effects of the gaugino mass nonuniversality on dark matter. Some features of the effects of gaugino mass nonuniversalities have already been discussed in the literature ³⁴⁾ and we review here the more recent developments ¹¹⁾. The techniques used in the analysis are as discussed in Ref. ³²⁾ and in the analysis we impose the $b \rightarrow s + \gamma$ constraint ³⁵⁾. In Fig.1 we plot the scalar $\chi - p$ cross-section as a function of the neutralino mass for the case of GUT scale nonuniversalities with values of c_{24} in the range -0.1 to 0.08. One finds that the scalar cross-section is enhanced for negative values of c_{24} just as one would expect from the general discussion above because it is for the case of c_{24} negative that μ becomes small. One finds that in general the scalar cross-section increases systematically as $|c_{24}|$ increases for negative values of c_{24} and an enhancement of the scalar cross-section by as much as a factor of 10

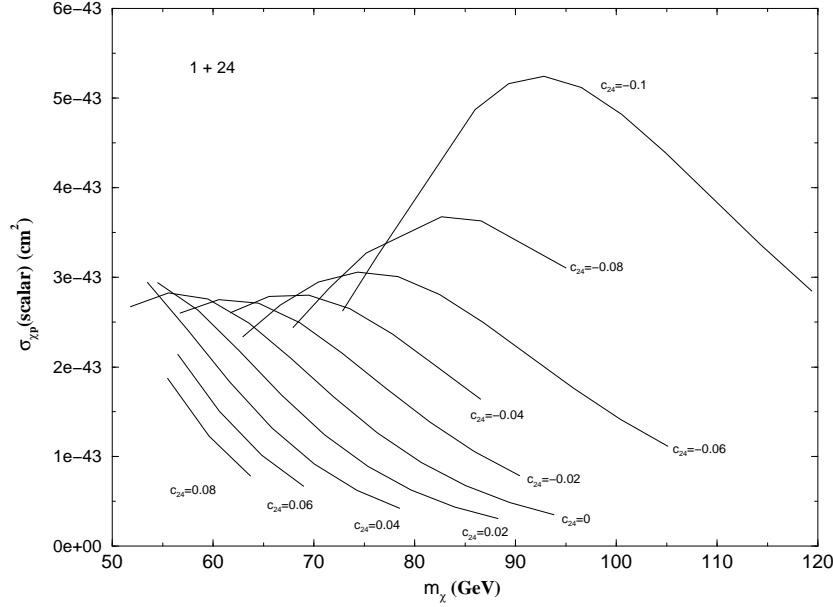


Figure 1: $\sigma_{\chi p}(\text{scalar})$ vs m_χ when $m_0 = 51 \text{ GeV}$, $\tan \beta = 10$, $A_t/m_0 = -7$ and c_{24} takes on various values (Taken from Ref. 11).

can be gotten relative to the universal case of $c_{24} = 0$. One also finds an enhancement of the allowed range of the neutralino mass consistent with the constraints. In Fig.2 we plot the maximum and the minimum of the scalar cross-section as a function of the neutralino mass for the case of GUT scale nonuniversalities where the nonuniversalities arise from the 200 plet representation with $c_{200} = 0.1$ when the other parameters are varied over their assumed naturalness range. The current experimental limits from DAMA ¹⁾ and from CDMS ²⁾ are also plotted. Further, the current limits would certainly be significantly improved in other dark matter detectors in the future ^{2, 3, 4)} and in Fig.2 we also plot the expected limits from future CDMS, and from GENIUS ⁴⁾. One finds that the current experiment does constrain the theory in a small region of the parameter space. Further, the expected sensitivity in future experiment, i.e., in CDMS and in GENIUS will explore a major part of the parameter space of this model. We also note that the inclusion of nonuniversality significantly increases the allowed range of the neutralino parameter space.

2.7 Dark Matter on D Branes

Nonuniversality of gaugino masses is rather generic in string theory. However, the specific nature of the nonuniversality will depend on the details of the compactifi-

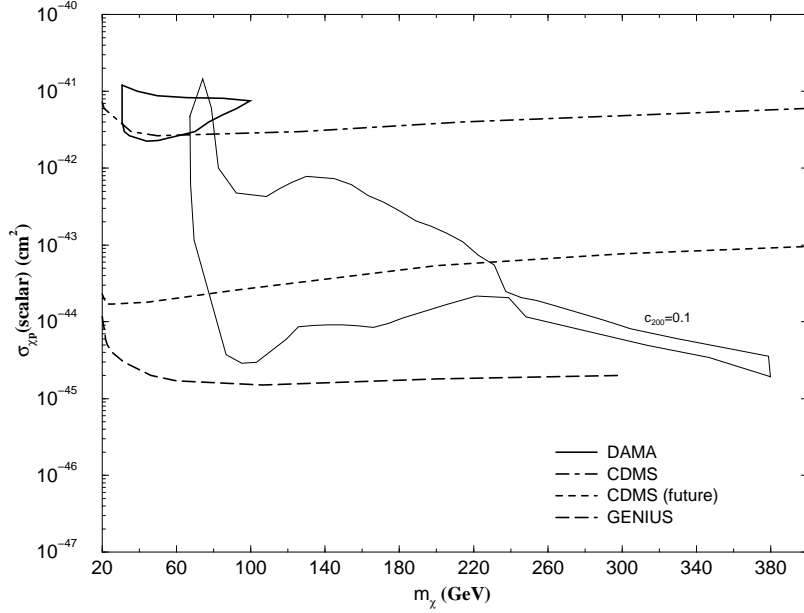


Figure 2: *The maximum and the minimum curves of $\sigma_{\chi p}(\text{scalar})$ vs m_χ when $c_{200} = 0.1$ and SUSY parameters are varied over the naturalness domain (Taken from Ref. 11).*

cation. We discuss here the effects of gaugino mass nonuniversality on dark matter in the context of D brane models. The possibility of nonuniversal gaugino phases in brane models arises from the choice of embedding of the different gauge groups of the Standard Model on different branes. One may consider, from example, models that arise from Type IIB string compactified on a six-torus $T^2 \times T^2 \times T^2$ which contains 9 branes, 7_i and 5_i ($i=1,2,3$) branes and 3 branes. Not all the branes can be present simultaneously due to the constraint of N=1 supersymmetry which requires that one has either 9 branes and 5_i ($i=1,2,3$) branes or 7_i ($i=1,2,3$) branes and 3 branes. In the following we will make the choice of embedding on 9 branes and 5 branes ²³). One of the major problems in developing a sensible string phenomenology is that the mechanism of supersymmetry breaking in string theory is still lacking. However, some progress can be made by use of an efficient parametrization of supersymmetry breaking. Here we use the parametrization where the breaking of supersymmetry arises from the breaking generated by the dilaton and the moduli VEV's of the following form ³⁶) $F^S = \sqrt{3}m_{3/2}(S + S^*)\sin\theta e^{-i\gamma_S}$, $F^i = \sqrt{3}m_{3/2}(T_i + T_i^*)\cos\theta_i e^{-i\gamma_i}$. We consider now a specific 9-5 brane model. Here one embeds the $SU(3)_C \times U(1)_Y$ gauge group on 9 branes and $SU(2)_L$ gauge group on a 5_1 brane. The alternative possibility of embedding the Standard Model gauge group on five branes is discussed in the last two papers of Ref. ²²). For the 9- 5_1 brane model the soft SUSY breaking

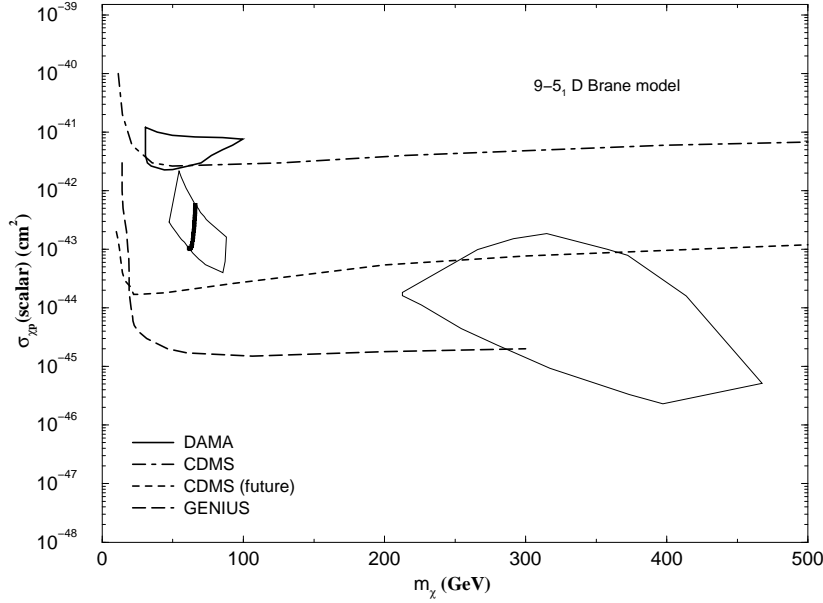


Figure 3: *The maximum and the minimum curves of $\sigma_{\chi p}(\text{scalar})$ vs m_χ for the 9-5 D brane model when $c_{200} = 0.1$ when $m_{3/2}$ ranges up to 2 TeV, $\tan \beta$ ranges up to 25, and θ lies in the range 0.1-1.6. (Taken from Ref. 11).*

sector of the theory is given by 36, 23)

$$\begin{aligned} \tilde{m}_1 = \tilde{m}_3 &= \sqrt{3}m_{3/2}\sin\theta e^{-i\gamma_S} = -A_0; \quad \tilde{m}_2 = \sqrt{3}m_{3/2}\cos\theta e^{-i\gamma_i} \\ \tilde{m}_9^2 &= m_{3/2}^2(1 - 3\cos^2\theta\Theta_1^2); \quad \tilde{m}_{95_1}^2 = m_{3/2}^2(1 - (3/2)\cos^2\theta(1 - \Theta_1^2)) \end{aligned} \quad (21)$$

Here $\theta(\Theta_i)$ is the Goldstino direction in the dilaton S (moduli T_i) VEV space. We discuss now dark matter on D branes. In Fig.3 we give a plot of the scalar $\chi - p$ cross section as a function of the neutralino mass for the 9 – 5₁ D brane model. One of the interesting feature of the D brane model is that the scalar masses are in general not universal. However for $\Theta_1 = 1/\sqrt{3}$ one has $m_9 = m_{95_1}$ and the scalar masses are universal although the gaugino masses are still nonuniversal. Since we are mostly interested here in investigating the effects of nonuniversalities of the gaugino masses in this analysis, we impose universality of the scalar masses and set $\Theta_1 = 1/\sqrt{3}$. In Fig.3 we give a plot of the minimum and the maximum of the scalar $\chi - p$ cross section under this constraint. One finds that under the assumed constraints the allowed domain of the parameter space has the general features which are similar to the GUT scale nonuniversalities. One common feature is that the allowed domain of the parameter space is extended close to 500 GeV. One may note that if in addition to the constraint $\Theta_1 = 1/\sqrt{3}$ one also sets $\theta = \pi/6$ one finds also universality of the gaugino masses. This situation is exhibited by the vertical dark line in the enclosed

region on the left hand side in Fig.3.

3 Conclusion

In this paper we have given a brief review of the recent theoretical developments in the analyses of supersymmetric dark matter. Our emphasis has been in exploring the effects of uncertainties of the input data and the effects of nonuniversalities of the gaugino masses on dark matter analyses. It is found that the uncertainties of the wimp velocities can change detection rates by up to factors of 2-3 while the uncertainties in quark masses and densities can change the $\chi - p$ cross-section by up to factors of 5 in either direction. The effects of gaugino mass nonuniversalities on dark matter analyses is found to be quite dramatic. It is seen that gaugino mass nonuniversalities can increase the Higgsino components of the LSP and significantly increase the $\chi - p$ cross-section from scalar interactions and also increase the allowed range of the LSP consistent with relic density constraints. Thus an increase in the scalar $\chi - p$ cross-sections by up to a factor of 10 can occur while the allowed range of the neutralino masses can move up to 500 GeV consistent with the relic density constraints. Data from current dark matter experiments is beginning to put constraints on models with nonuniversalities. These constraints will become more severe as the sensitivity of dark matter experiments increase in the future.

Acknowledgements

This research was supported in part by NSF grant PHY-9901057.

References

1. R. Belli et.al., "Search for WIMP annual modulation signature: results from DAMa/NAI-3 and DAMa/NAI-4 and the global combined analysis", DAMA collaboration preprint INFN/AE-00/01, 1 February, 2000.
2. R. Abusaidi et.al., "Exclusion Limits on WIMP-Nucleon Cross-Section from the Cryogenic Dark Matter Search", CDMS Collaboration preprint CWRU-P5-00/UCSB-HEP-00-01 and astro-ph/0002471.
3. N. Spooner, "Progress on the Boulby Mine Dark Matter Experiment", Talk at the conference "Sources and Detection of Dark Matter/Energy in the Universe", Marina Del Rey, CA, February 23-25, 2000.
4. L. Baudis, et.al., "GENIUS, A Supersensitive Germanium Detector System for Rare Events: Proposal", MPI-H-V26-1999, hep-ph/9910205.

5. P. Belli, R. Bernbei, A. Bottino, F. Donato, N. Fornengo, D. Prospero, and S. Scopel, Phys. Rev. **D61**, 023512(2000).
6. M. Brhlik and L. Roszkowski, Phys. Lett. **B464**, 303(1999).
7. A. Corsetti and P. Nath, hep-ph/9904497 (to appear in Mod. Phys. Journ.)
8. M. Kamionkowski and A.. Kinkhabwala, Phys. Rev.**D57**, 3256(1998).
9. A. Bottino, F. Donato, N. Fornengo and S. Scopel, hep-ph/9909228.
10. J. Ellis, A. Ferstl and K.A. Olive, hep-ph/0001005.
11. A. Corsetti and P. Nath, hep-ph/0003186.
12. M. Brhlik, D.J. Chung, and G. Kane, hep-ph/0005158.
13. T.Falk, K.Olive and M. Srednicki, Phys. Lett. **B354**, 99(1995); T. Falk, A. Ferstl and K. Olive, Phys. Rev.**D59**, 055009(1999).
14. U. Chattopadhyay, T. Ibrahim and P. Nath, Phys. Rev. **D60**,063505(1999); T. Falk, A. Ferstl and K. Olive, hep-ph/9908311; S. Khalil and Q. Shafi, Nucl. Phys. **B564**, 19(1999); K. Freese and P. Gondolo, hep-ph/9908390; S.Y. Choi, hep-ph/9908397; S. Khalil, hep-ph/9910408.
15. P. Nath and R. Arnowitt, Phys. Rev.**D56**, 2820(1997); E. Accomando, R. Arnowitt and B. Datta, and Y. Santos, hep-ph/0001019.
16. J. Ellis, T. Falk, K. A. Olive, M. Srednicki, CERN-TH-99-146, hep-ph/9905481 and the references therein.
17. A.H. Chamseddine, R. Arnowitt, and P. Nath, Phys. Rev. Lett. **49**, 970(1982); For a review see, P. Nath, R. Arnowitt and A.H. Chamseddine, Applied N=1 supergravity, Trieste Lectures, 1983(World Scientific, Singapore,1984); H. P. Nilles, Phys. Rep. **110**, 1(1984); S. Abel et.al., hep-ph/0003154.
18. W. Freedman, astro-ph/9909076
19. C. Lineweaver, astro-ph/9909301.
20. E. Gates, G. Gyuk and M.S. Turner, Phys. Rev. **D53**, 4138(1996).

21. G.R.Knapp et.al., Astron. J. **83**, 1585(1978); F.J. Kerr and D. Lynden-Bell, Mon. Not. R. Astr. Soc. **221**, 1023(1986); J.A.R. Caldwell and J.M. Coulsen, Astron. J. **93**, 1090(1987).
22. T. Ibrahim and P. Nath, Phys. Lett. **B 418**, 98(1998); Phys. Rev. **D57**, 478(1998); Phys. Rev. **D58**, 111301(1998); T. Falk and K Olive, Phys. Lett. **B 439**, 71(1998); M. Brhlik, G.J. Good, and G.L. Kane, Phys. Rev. **D59**, 115004 (1999); A. Bartl, T. Gajdosik, W. Porod, P. Stockinger, and H. Stremnitzer, Phys. Rev. **60**, 073003(1999); T. Falk, K.A. Olive, M. Prospelov, and R. Roiban, Nucl. Phys. **B560**, 3(1999); S. Pokorski, J. Rosiek and C.A. Savoy, Nucl. Phys. **B570**, 81(2000); E. Accomando, R. Arnowitt and B. Datta, hep-ph/9907446; M. Brhlik, L. Everett, G. Kane and J.Lykken, Phys. Rev. Lett. **83**, 2124, 1999; hep-ph/9908326; E. Accomando, R. Arnowitt and B. Datta, Phys. Rev. **D61**, 075010(2000).
23. T. Ibrahim and P. Nath, Phys. Rev. **D61**, 093004(2000).
24. S. Mizuta and M. Yamaguchi, Phys. Rev. Lett. **B298**, 120(1993).
25. S. K. Soni and H. A. Weldon, Phys. Lett. **B126**, 215(1983); V. S. Kaplunovsky and J. Louis, Phys. Lett. **B306**, 268(1993); D. Matalliotakis and H.P. Nilles, Nucl.Phys.**B435**, 115(1995); M. Olechowski and S. Pokorski, Phys.Lett. **B344**, 201(1995); N. Polonski and A. Pomarol, Phys.Rev.**D51**,6532(1995).
26. J. Ellis, K. Enqvist, D. V. Nanopoulos, and K. Tamvakis, Phys. Lett. **155B**, 381(1985); M. Drees, Phys. Lett. **B158**, 409(1985); T. Dasgupta, P. Mamales, P. Nath, Phys.Rev. **D52**, 5366(1995); D. Ring, S. Urano and R. Arnowitt, Phys. Rev. **D52**,6623(1995).
27. G. Anderson, C.H. Chen, J.F. Gunion, J. Lykken, T. Moroi, and Y. Yamada, hep-ph/9609457; G. Anderson, H. Baer, C-H Chen and X. Tata, hep-ph/9903370; K. Huitu, Y. Kawamura, T. Kobayashi and K. Puolamaki, hep-ph/9903528.
28. P. Nath and R. Arnowitt, Phys.Lett.**B289**,368(1992); R. Arnowitt and P. Nath, Phys.Rev. Lett. **69**,725(1992); Phys. Rev.**D54**, 2374(1996).
29. H. Goldberg, Phys. Rev. Lett. **50**, 1419(1983); J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, Nucl. Phys. **B238**, 453(1984).

30. R. Arnowitt and P. Nath, Phys. Lett. **B299**, 103(1993); Phys. Rev. Lett. **70**, 3696(1993); H. Baer and M. Brhlik, Phys. Rev. **D53**, 597(1996); V. Barger and C. Kao, Phys. Rev. **D57**, 3131(1998).
31. A small sample of papers in direct detection in MSSM consists of: W.A. Goodman and E. Witten, Phys. Rev. **D31**, 3059(1983); G. Greist, Phys. Rev. Lett. **61**, 666(1988); J. Ellis and R. Flores, Phys. **B263**, 259(1991); A. Bottino et.al. Astro. Part. Phys. **1**, 61(1992); M. Drees and M. Nojiri, Phys. Rev. **D48**, 3483(1993); V.A. Bednyakov, H.V. Klapdor-Kleingrothaus and S.G. Kovalenko, Phys. Rev. **D50**, 7128(1994).
32. R. Arnowitt and P. Nath, Phys. Rev. Lett. **70**, 3696(1993); *ibid*, 74, 4592(1995); G. Kane, C. Kolda, L. Roskowski and J. Wells, Phys. Rev. **D49**, 6173(1994); H. Baer and M. Brhlik, Phys. Rev. **D53**, 597(1996).
33. G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rep. **267**, (1995)195.
34. K. Greist and L. Roskowski, Phys. Rev. **D46**, 3309(1992); M. Drees and M. Nojiri, Phys. Rev. **D47**, 376(1993); S. Mizuta, D. Ng and M. Yamaguchi, Phys. Lett. **B 300**, 96(1993).
35. P. Nath and R. Arnowitt, Phys. Lett. **B336**, 395(1994); F. Borzumati, M. Drees, and M.M. Nojiri, Phys. Rev. **D51**, 341(1995); V. Barger and C. Kao, Phys. Rev. **D57**, 3131(1998); H. Baer, M. Brhlik, D. Castano and X. Tata, Phys. Rev. **D58**, 015007(1998).
36. I. Ibanez, C. Munoz and S. Rigolin, Nucl. Phys. **B536**, 29(1998) and the references quoted therein.